Performance of a Day/Night Water Heat Storage System for Heating and Cooling of Semi-Closed Greenhouses in Mild Winter Climate

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Keywords: heat exchanger, energy saving, air flow, tomato, double cover

Abstract

A novel system for heating/cooling greenhouses based on air/water heat exchangers connected to a thermally stratified water storage tank was tested in a small greenhouse compartment at the Experimental Station of the Cajamar Foundation in Almería, Spain. The system maintained a closed greenhouse (no natural ventilation) throughout the winter and spring during which a truss tomato crop was grown. Atmospheric CO_2 concentration could be maintained during the daytime allowing for greater net photosynthesis in relation to a reference greenhouse in which traditional natural ventilation was used to control temperature and humidity. Three fine wire heat exchangers (Fiwihex®) were installed 1 m above the crop when at full development. The heat exchangers allowed for a very efficient transfer of the sensible and latent heat accumulated in the compartment. During the winter, the daytime temperatures were maintained below the ventilation set point (30°C). During the night, the system was able to maintain temperatures above the heating set point (12°C), with stored warm water temperatures between 15 and 17°C after clear days. After cloudy days, with water temperatures between 11 and 13°C, the system could always keep a temperature gradient with the exterior of 4-6°C, enough to maintain greenhouse air temperatures above 8ºC the entire night. When seasonal night air temperatures exceeded the heating set point, the hot water at the top of the tank was cooled to the wet bulb temperature by means of an open cooling tower. The cooled water was used for cooling the greenhouse, which allowed for closing the greenhouse for a longer period. The water condensate during the cooling mode, allowed for a high water saving and maintained the relative humidity very constant during the day (around 80%). During the night, humidity was kept at 90% without ever reaching saturation.

INTRODUCTION

Different systems have been proposed and tested during the last three decades of the past century which focused on saving energy, taking advantage of the basic nature of the greenhouse as a solar collector (e.g. Garzoli and Shell, 1984). Instead of discharging the surplus sensible and latent heat by means of natural ventilation, these systems took advantage of closing the greenhouse ventilators, extracting and storing the excess heat for its later use during the cold season (long term storage), or the following night (short term storage) (Daunicht, 1975; Levav and Zamir, 1987; DeJong et al., 1993). The other major advantages of a semi-closed greenhouse is to limit pests from entering and maintaining elevated CO_2 concentrations in the greenhouse air to increase the yield (Nilsen et al., 1983).

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These systems have been developed for commercial purposes during the last decade, first in cold greenhouse areas (The Netherlands, Canada, etc.) and then in warm areas. The commercial systems used in many cold areas use high efficiency heat exchangers, which allow for long term heat storage during the warm months within existing confined ground aquifers for storage and extraction during the warm and cold season respectively. In warm areas, systems have recently been tested that use short term storage (day/night) in water tanks (Zaragoza et al., 2007).

The present work is about the performance of a novel system for cooling/heating a small greenhouse compartment in Almería to extend the closed period with short term energy storage in a thermally stratified water tank and a cooling tower that transfers energy from water to ambient air.

METHODS AND MATERIALS

In the Experimental Station of the Cajamar Foundation, and based on the predictions and estimations obtained from the HortiAlmería model (see other work presented in this meeting "Design and Modelling of Novel System for Heating and Cooling of Semi-Closed Greenhouses in Mild Winter Climate Areas based on Fine Wire Heat Exchangers and Water Storage on Tank" by Bailey et al.), a novel system for cooling/heating semi-closed greenhouses with high efficiency fine wire heat exchangers, based on short term heat storage in a water tank was designed and implemented in a small greenhouse compartment. The main part of the system (control room, storage tank, cooling tower, etc.) was designed to condition 960 m^2 in the future. But for preliminary tests, only one compartment of 160 m^2 has been conditioned the first year with in total three heat exchange (Fiwihex®; Hidro Systems Holland B.V.) units and a total water circulation capacity of 5.25 $m^3 h^{-1}$

The water in the storage silo is always in "open" contact with air; therefore the material used for piping and system components is stainless steel, PVC or other non-corrosive materials. The main parts of the system have been installed in a sea container (dimensions, cm, 606×244×259) and assembled previously to the final location of the equipment.

The main goal is to keep the greenhouse as closed as possible, which is necessary to keep the CO_2 concentration at high levels during the daytime (800-1000 ppm). The greenhouse has been provided with heat exchange units and a condensate collecting system to avoid excess humidity. The condensate is very clean and is used for watering plants. The following scheme is an overall diagram of the system including the open cooling tower, the water silo, the mixing group and control system and the heat exchangers (Fig. 1).

Three Fiwihex® heat exchangers, which are a combination of a heat exchanger and a cross flow ventilator for forced air movement, were mounted inside a galvanized steel frame. They were installed one meter above the top of a well-developed tomato crop, with a condensate collector which was a tray mounted beneath to collect condensate (Fig. 2) Large quantities of heat can be transferred with only a small temperature difference as each heat exchanger is equipped with a large surface area for contact between air and water. The units have a maximum cooling capacity under practical circumstances of 300-400 W m^{-2} of greenhouse (more technical details in http://www.hsh-fiwihex.com/).

A sea container was used as control room (Fig. 2). A 60 m^3 silo with diameter of 4.55 m and height of 3.88 m was used for storage of both cold and warm water (Fig. 2). The bottom ring of the silo was coated with a durable waterproof liner (Aquatex®; Genap Folieconstructies). The silo was insulated with 50 mm thick curved expanded polystyrene sheets (type EPS 100 RE). These sheets were placed between the silo liner and the galvanized steel plating. The floor was also insulated in the same manner. An insulating green-coloured PVC sheet was installed on top of the water surface providing protection from rainfall. In thermal storage, water has to be added and removed to minimize disturbances and mixing. This requires two diffusers, one to withdraw cold water from the bottom of the storage and the other to introduce warm water at the top. The diffusers permitted a uniform flow across the entire horizontal plane of the storage. The diffusers that have been designed, constructed and implemented in the silo consist of an octagonal "ring" made from sections of perforated plastic pipe joined by 45º bends (see other work presented in this meeting "Design and Modelling of Novel System for Heating and Cooling of Semi-Closed Greenhouses in Mild Winter Climate Areas based on Fine Wire Heat Exchangers and Water Storage on Tank" by Bailey et al.). The silo has 4 temperature sensors (PT-100; Jumo Instruments Co Ltd.) at different heights to monitor thermal stratification.

A 4 kW open cooling tower (Fig. 2) with a capacity of 40 L s^{-1} with a temperature difference of 6°C (35°C in, 29°C out) was installed and connected to the system for heat transport to ambient. This cooling tower allowed for cooling of the hot water accumulated at the top of the silo when night temperatures did not require for delivering the heat inside the greenhouse, and thus it provided an extra time period for cooling and keeping the greenhouse closed.

The system was controlled with a programmable steering and control unit for all functions of the Fiwihex® system. The system has 4 operation modes: Mode 1: Standby; Mode 2: Cooling greenhouse using the heat storage; Mode 3: Heating greenhouse using the heat storage; Mode 4: Cooling heat store using the cooling tower.

The energy exchange inside the greenhouse (convection plus conduction due to water condensation) was provided by the three Fiwihex® heat exchangers. In cooling situation (Mode 2), cold water was removed from the lower part of the energy storage and transferred to the Fiwihex® heat exchangers. Simultaneously, the warm greenhouse air passed through the Fiwihex®. The heated water flowed back to the upper part of the energy storage. A temperature gradient was produced during the day in water between the lower and upper part of the energy storage. When heating was required the water was removed from the upper part and returned to the lower part of the storage after heating the greenhouse (Mode 3). When night air temperatures were greater than the heating set point, and the water temperature in the storage was 4°C above the exterior temperature, then Mode 4 was activated to cool the water in the heat storage and gain cooling capacity for the next day.

The set points established for the system were: (i) Ventilation set point: 30°C; (ii) Cooling set point: 20°C in winter (at this temperature the system starts sending cold water flow which progressively increases depending on the inside temperature and the cold water temperature). This set point was established slightly low to collect enough energy (warm water) for the night during the winter. In the spring time, it was increased to 24°C; (iii) Heating set point: 12°C except during a period (one hour before dawn and one hour after dawn) which was increased to 15°C to activate the plant; (iv) CO_2 enrichment to 800 ppm for vents completely closed, 400-800 ppm if vents open less than 10% and 400 ppm for vents open>10%.

The heat exchanger fans were activated every time the system started cooling or heating and were otherwise off. On cloudy nights they were activated to move the air in the compartment and prevent condensation on plants and fruits.

Inside the compartment, dry and wet bulb air temperatures (aspirated psychrometer with two thermistors 3K), and CO_2 concentration were continuously monitored and averaged every 5 minutes. In one of the Fiwihex® units, the temperature of the air and water before and after the heat exchange process were continuously monitored, as well as, all the energy consumed by the heat exchanger, circulation pump and cooling tower, and CO_2 consumed during the experimentation period.

The tomato crop was transplanted on 14 July 2009, and it was intended to start evaluating the system in October. Due to several leakage problems in the water silo which required the double diffuser to be disconnected and removed, the system could only be activated by 28 November. The greenhouse compartment was kept closed during the daytime with ventilation only at night to decrease humidity for 90% of the daytime until 30 May, when the system was unable to maintain 30°C during the mid-day hours. At that time addition of CO_2 was reduced, as the ventilators were opened more than 10%. On 23

February a second tomato crop was inter-planted in the compartment, and the previous crop was removed on the 3 May. The second crop was ended on 30 June.

RESULTS AND DISCUSSION

Performance of the System during the Winter Months

The system in winter on clear days stored sufficient energy in the silo and good thermal stratification was achieved (Fig. 3). The data correspond to 4 December 2009. In Figure 3 the double diffuser system seems to be performing according as expected without creating much turbulence, hence allowing for a good separation between hot and cold water. During the daytime, when cooling mode was active, the returning hot water accumulated mainly at the top and especially, at the middle part of the tank, which within few hours increased the water temperature from 9°C to almost 14°C. Until midnight, there was no heating demand from the greenhouse as the outside air temperature was not less than 12°C. After several cloudy days, the system collected little or no energy and the thermal stratification was lost, while on cloudy days followed by a cloudy night, for the Almería conditions, neither cooling nor heating was required in the greenhouse (system under mode 1, temperatures comprised mostly between 12 and 20°C).

Figures 4, 5, and 6 summarize that the heat exchangers were affecting the climate inside the closed compartment for the 28 January 2010, which was a clear day and clear night.

For most circumstances, the daily relative humidity inside and outside the closed compartment during the winter and spring followed the trend shown in Figure 4. Since the greenhouse ventilators were closed, the relative humidity was increased and ranged between 70 and 90%, but saturation was never achieved. During the day the heat exchangers were condensing a large part of the water vapour transpired by the plants which prevented saturation and during the night the greenhouse air was heated such that saturation was never achieved.

During the night (Fig. 5), the system had the heating mode activated and the set point temperature of 12°C was maintained throughout with a temperature increase of around 3°C in relation to the outside temperature. The adjacent ventilated compartment maintained a temperature almost equal to the outside temperature. During the daytime the cooling mode was active and the temperature was kept below 25°C and to very similar values to an adjacent naturally ventilated compartment. After sunset, the heating mode was again activated, using the energy accumulated from the day and, unlike in the adjacent open compartment, the temperature drop was not as fast as in the ventilated unheated adjacent greenhouse. The plant temperature remained at very similar values to the ambient temperature during the night and 1-2°C lower, during the daytime. There was good transpiration from the crop which was not affected by the high RH, and was stimulated by the high CO_2 concentration and the airflow created by the fans inside the compartment.

Temperatures of the air immediately before it entered the heat exchange units and the temperature immediately after the air emerged from the heat exchanger are shown in Figure 6. During the night period the air leaving the heat exchangers had a temperature that ranged from 12 to 13°C, which was approximately the average ambient temperature that was maintained (Fig. 6). During the period the pump was supplying water at a high rate (80%). During the daytime, the pump was not supplying such a high water rate (49.5%) since it was not necessary as the ambient temperature was maintained at values well below the ventilation set point and that is the reason why the difference between the air in and the air off temperatures is very low on this period. During the night the water delivers very little energy to the air since the temperature gradient to be maintained is not very high (≈3°C), therefore, the “water out” temperature is only slightly cooler than the “water on” temperature. However, during the day, a large amount of energy is transferred to the water from all the sensible and latent heat accumulated in the closed compartment, and at the peak the water is cooled to almost 6°C.

Performance of the System during the Spring Months

On 7 April 2010, the cooling tower was activated, so that the warm water accumulated in the silo would dissipate heat to the outside air in order to have cold water available for the next day. The cooling tower mode was activated whenever the average temperature of the water in the silo was more than 2°C greater than the ambient wet bulb temperature. Generally, one hour was sufficient time to cool most of the volume of the tank, except for the very top water layer (Fig. 1).

The water temperature at four different heights in the silo from bottom to top is shown for 1 May 2010 (Fig. 7). The cooling tower was activated twice on this day, one hour just before noon, in which the nearly all the water was cooled 1°C, to the wet bulb external temperature; and then again in the afternoon, this time the water was cooled 3°C. During the hours in which the cooling mode was on, the temperature of the water in the tank was increasing mostly at the middle of the silo. First in the lower layer, then in the upper layer, and more slowly in the extreme bottom and top layers.

It was possible to maintain the greenhouse almost completely closed until the 30 May. During the month of May, with very clear days, the ventilators had to open during short periods of air temperature greater than 30°C, near noon. However, they opened less than 10% so CO_2 injection was not restricted. The climate inside the closed compartment on an average clear spring day of Almería (1 May 2010) reached air temperature of nearly 30°C, and a maximum temperature difference of 8.7°C compared to the outside temperature, and 5.1°C compared to an adjacent, well ventilated greenhouse containing the same crop. CO_2 concentrations remained between 750 and 1000 ppm during the daytime (between 750 and 1000 ppm) allowing for greater net photosynthesis (data not shown).

During the daytime, in summer, during cooling mode, the water absorbed much energy and increased a maximum of 5.3°C (heat absorbed by convection and due to water condensation), and the air cooled a maximum of 3.2°C (Fig. 9). The large amount of energy absorbed by the water during the high radiation months demonstrated that a cooling tower was necessary for the greenhouse to be closed during the early spring and possibly autumn months

CONCLUSIONS

A novel climate control system that was based on the use of high efficiency heat exchangers (FiwiHex®), a single day/night thermal storage tank, and an open cooling tower was tested for the Almería conditions during the winter and spring months in a small (160 m^2) greenhouse compartment. The system was able to maintain the greenhouse almost completely closed during the daytime from December until the end of May. In general terms, the climate inside the compartment was warmer and more humid during the day and the night in winter (due to the use of heat accumulated during the day), than in an adjacent greenhouse managed with natural ventilation. During the spring, the cooling tower had to be used during the night to provide cooling capacity for the next day, again providing a warmer and more humid greenhouse climate than in the adjacent greenhouse.

The single storage tank, with double diffusers for water collection/delivery from/to the greenhouse, respectively, performed according to design, with good stratification achieved during clear days, which allowed for the use of the energy at night during the winter.

ACKNOWLEDGMENTS

This research was supported by the EU collaborative project Euphoros (Efficient use of inputs in protected Horticulture) 7th Framework Program KBBE-2007-1-2-04.

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Figures

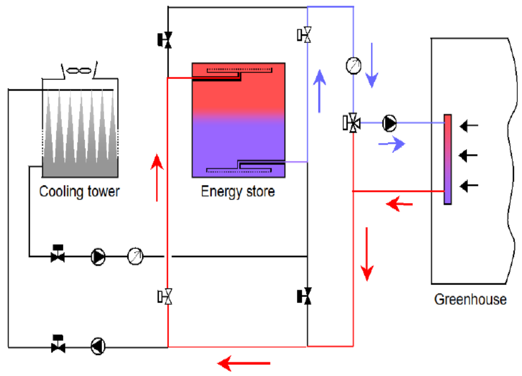

Fig. 1. Overall diagram of the system.

Fig. 2. Picture of one heat exchanger with the condensate water collection device.

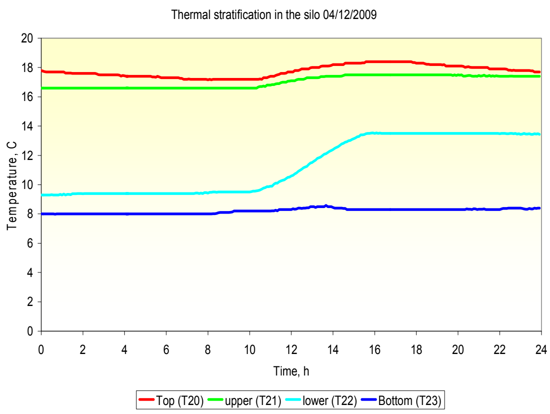

Fig. 3. Thermal stratification in the storage tank on a clear winter day (4/12/2009).

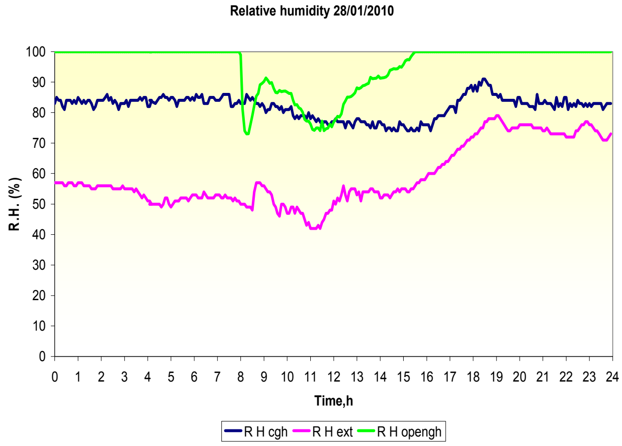

Fig. 4. Twenty-four hours evolution (28/1/2010) of the relative humidity in the closed compartment, open compartment and exterior.

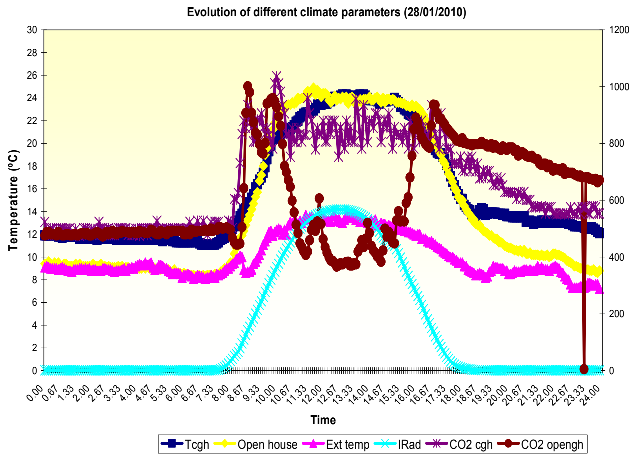

Fig. 5. Twenty-four hours evolution (28/1/2010) of ambient temperature, radiation and CO_2 concentration in the closed and open compartments on a clear winter day.

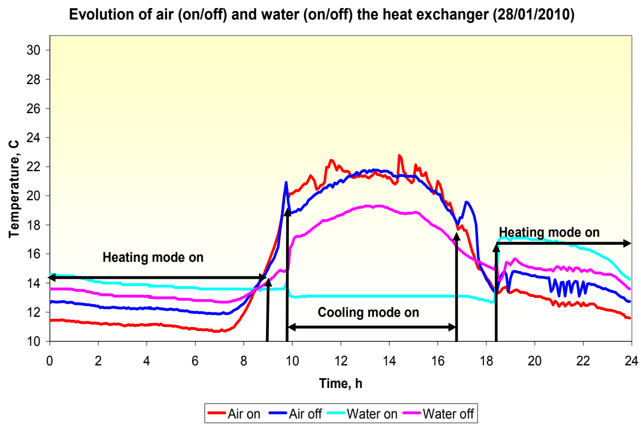

Fig. 6. Twenty-four hours evolution (28/1/2010) of the air and water (before and after the heat exchanger) on a clear winter day.

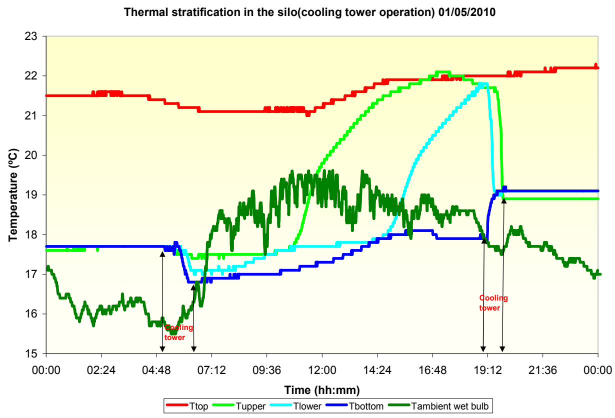

Fig. 7. Thermal stratification in the storage tank on a clear spring day (1/5/2010).

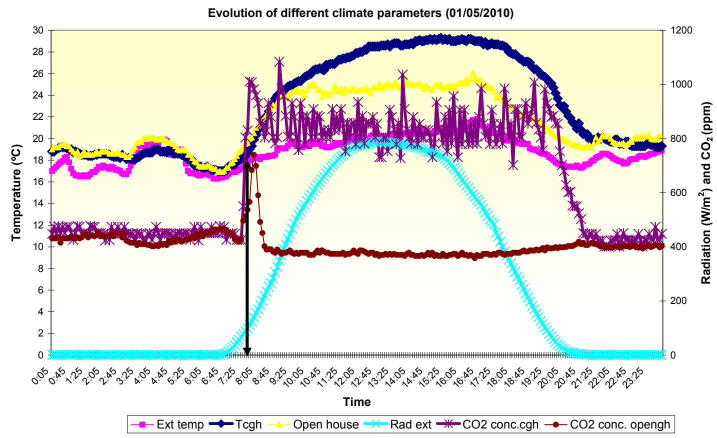

Fig. 8. Twenty-four hours evolution (01/05/2010) of ambient temperature, radiation and CO_2 concentration in the closed and open compartments on a clear spring day.

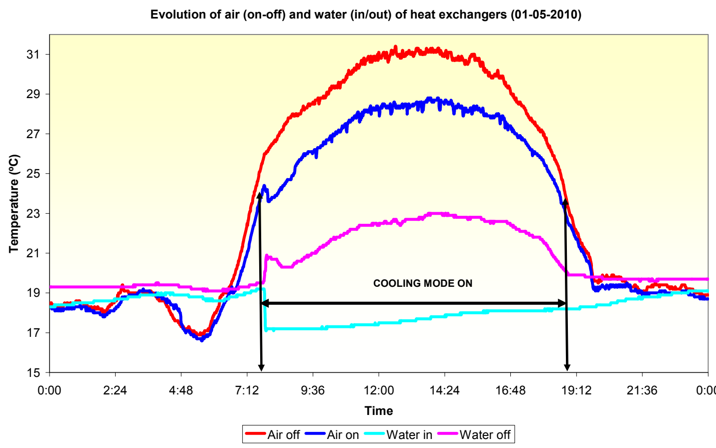

Fig. 9. Twenty-four hours evolution (01/05/2010) of the air and water (before and after the heat exchanger) on a clear winter day.